Mid-Frequency Scattering and Reverberation in a Very Shallow Water Environment

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LONG-TERM GOALS

The long-term goal of this research is development of computationally efficient physics-based methods for modeling propagation, scattering, and reverberation in shallow waters with complicated spatial and temporal variability of environmental parameters.

OBJECTIVES

Specific objectives of this research are to develop a model of reverberation for conditions (1 – 10 kHz, ~ 20 m water depth, ~ 10 km range) corresponding to the ONR Target and Reverberation Experiment performed on the spring 2013 (TREX2013), develop a code and conduct computer simulations with environmental inputs typical for the chosen location, and apply this model to analysis of available TREX2013 data, see [TREX13 web-site]. This report demonstrates capabilities of the developed codes based on Green's function modelling approach to provide extremely fast predictions of reverberation in a very shallow water environment, gives numerical examples for several relevant scenarios, discusses possibilities for a quantitative interpretation of reverberation data, presents tentative TREX2013 data-model comparisons, and suggests implications for future research.

APPROACH

The Green's function modelling approach, which was used in this project, allows fast estimations of reverberation in shallow water. The approach also addresses a basic science question: how far-field scattering solutions obtained for free space can be incorporated into reverberation in bounded and complicated environments, such as shallow water or deep-water waveguides, where effects of multiple scattering and interaction with boundaries and volume heterogeneities must be taken into account. A basic approach, its simplified first-order version and initial results, are based on models discussed in Ivakin (2010, 2011, 2012a, 2012b, 2013). A higher-order modification of this approach exploits ideas of a MFSB (Multiple Forward Single Backscatter) approximation developed by De Wolf (1971) for studying electromagnetic propagation and multiple scattering effects in a turbulent atmosphere. For description of such effects in acoustics of marine sediments, the MFSB-approach was applied in Ivakin (1999), and reformulated for the case of reverberation in a shallow-water waveguide in Ivakin (2008). Its further development is presented in Ivakin (2015a, 2015b).

The first-order approach provides a simple integral expression for the backscatter intensity, which has a factorized integrand comprised of two kernels, the two-way propagator and the scattering kernel. The propagator is a product of two local intensities, each being defined along one of the two ways of propagation. For rather complicated environments, generally depth-range-dependent, the local intensity can be calculated using available models and codes, e.g. PE, normal modes, ray-based, or other approximations. The scattering kernel is defined as a local volume scattering coefficient and exploits simple first-order solutions for far-field scattering from a heterogeneous volume in free (unbounded) space. It can be specified for sea-water column and seabed with continuum heterogeneity, such as spatial fluctuations of density and sound speed, and/or discrete randomly and sparsely distributed targets, such as gas bubbles, fish, shells, lenses-like inclusions, oil droplets, solid hydrate particles, and others, Ivakin (2010, 2011, 2012). Moreover, the scattering kernel can include a component due to contribution of roughness at an arbirary number of interfaces through the roughness scattering coefficient, the power spectrum, and a contrast factor at each interface. In more detail, this case is described in Ivakin (1998, 2015b, 2015c).

The approach is applicable, generally, for a complex environment with volume heterogeneity and interface roughness of arbitrary strengths and locations, and, therefore, it allows an estimation of potential contributions of different mechanisms of scattering. In particular, it can be used for analysis of reverberation in a complex TREX13 environment taking into account volume heterogeneity of both water column and the seabed.

Integral expression for the reverberation intensity can be generalized by treating the propagating kernel stochastically and accounting for multiple forward-scatter effects, using the MFSB approximation. According to this approach, the total field is presented as a sum of a multiple forward-scattered field and a single-backscattered field, or through correspondent components of the full Green's function. Despite of apparent similarity to the first-order expressions, the higher-order approach represents a substantial modification and improvement. The approach allows taking into account such multiple scattering effects, as the scintillations of propagated intensity, the two-way propagation coherence, and the related "backscattering enhancement" known also as "coherent backscatter" and "weak localization", see Ivakin (2015a, 2015b).

WORK COMPLETED

This work was initially proposed, Ivakin (2012b), for a two-year period, FY2013 and FY2014, and then as additional FY15 project, Ivakin (2014). By now, this work is generally completed. At initial stage, a simplified version of the reverberation model was considered, with a focus on bottom scattering mechanisms, to facilitate developing codes and conducting pre-test computer simulations, helping with planning the acoustic experiment and environmental ground truth measurements. Results of this work were presented in Ivakin (2013), and Hefner et al (2013a, 2013b). Then a more general model of reverberation was developed, Ivakin (2015a), and computer simulations were performed to demonstrate capabilities of the first-order Green's function modeling approach to provide fast estimations of reverberation, to show critical steps in the algorithm of these estimations, and to help analyze potential contributions of different mechanisms of scattering in shallow water environments (heterogeneous water column, rough and heterogeneous bottom). Several scenarios with different types of a layered mud/sand bottom were considered, applicable to very shallow water, as well as to more general shallow water environments, see e.g. ONR Workshop (2015). Input parameters for bottom

were chosen to be representative and typical for mud and sand sediments. Details and results of these simulations are discussed in Ivakin (2015b).

The final stage of this project was to refine the modeling approach, and to provide tentative model-data comparisons based on the developed models and appeared TREX2013 data. Recently some data became available as acoustic and environmental inputs for the models, see TREX13 web-site. First results of the data analysis are presented in Ivakin (2015b), and Hefner et al (2015a, 2015b, 2015c). A more detailed TREX13 data analysis is proposed for future work, as described in Ivakin (2015b). For instance, TREX13 sediments were very heterogeneous, and had a substantial lateral variability of the sediment type and composition, mostly due to variations in mud and shell content, see Hefner and Tang (2014). A quantitative analysis of the effect is being planned as a part of future TREX13 data analysis.

RESULTS

The developed modeling approach was refined and specified for TREX13 environment, geometry and other input parameters. Green's function magnitude was calculated using a PE code, Tang (2014), for parameters corresponing to a Pekeris waveguide with sand bottom, chosen as most relevant to TREX13 conditions and available by now acoustic data, Tang (2015):

Central frequency – 3450 kHz;
Frequency bandwidth – 100 Hz;
Water depth – 19 m;
Source depth – 17.8 m;
Receiver (FORA) depth – 16.9 m;
Azimuthal beamwidth – 2.6 deg;
Source Level (SL) – 200 dB.

Calculations for the penetration field within the sand bottom were made for depths down to 2 m below bottom surface. Acoustic parameters for water and sand were taken as follows:

	water	sand
Sound speed, (m/s)	1525	1630
Density (g/cm^3)	1	2.0
Attenuation (loss tangent)	0	0.01

The algorithm for calculations of reverberation, specified for the TREX scenario, includes three steps. The first step, in contrast with preliminary simulations, considers a more general case of bistatic geometry, considering different locations of the source and receiver. The Green's function magnitude was pre-calculated for refined input parameters, given above. It is important that the algorithm requires calculations only at one (central) frequency.

The second step of the algorithm was also refined taking into account the fixed-fixed source-receiver geometry of the TREX13 reverberation measurements and a broad-band frequency filter (100 Hz) chosen for the TREX13 reverberation data processing, Yang et al (2014). This case requires a technique for smoothing strong oscillations of the propagation intensity, which differs from that used in preliminary simulations. It takes into account a range-dependent scales in interferencial structure of

the broad-band field in shallow water waveguides. In this case the range span for the smoothing is range dependent as well. More details on this technique are described in Ivakin (2015b).

The third step of the algorithm provides extremely fast evaluation of TREX13 reverberation using range-depth dependence of single-frequency Green's function intensity pre-calculated for this environment and smoothed in correspondence with the above-described technique. The integration for the scattered intensity was performed over a horizontal cross-section of the scattering (ensonified) volume, with a span of ranges and a span of azimuthal angles based on the system directivity and the radiated pulse duration, Ivakin (2015b).

Reverberation caused by bottom volume heterogeneity, as well as volume reverberation from scatterers in water column, was calculated and a tentative model/data comparison for a sub-set of TREX reverberation data was performed. The data sub-set used here is limited to a published example of TREX reverberation data, Hefner and Tang (2014), presented in some more detail in Yang et al (2014), see TREX13 Web-site. This example includes only one frequency sub-band (3400÷3500 Hz), one azimutal look angle, and two runs, Run #17 (23 April 2013) and Run #79 (9 May 2013). The data are shown in Figure 1, where a normalized reverberation intensity, Reverberation Level (RL) corrected for Source Level (SL), i.e. RL – SL, is presented. It is seen that the data shown in Figure 1 are somewhat different. This difference might represent an effect of environmental changes resulted from a storm occurred in the area around 1 May 2013. The following calculations and results of model-data comparisons, presented in Figures 2-7, give a tentative interpretation of this effect.

The model suggests that reverberation is caused by volume scattering either in water column or in the sediment. The contribution of bottom roughness can be considered in a way similar to shown in preliminary simulations, Ivakin (2015b). Typical values for the only free parameter of the model, the scattering strength per unit volume, M_V, were used to provide a reasonably good fit between model results and the data. First, reverberation from water column was considered. The results for before storm model-data comparison is shown in Figure 2. Generally, it shows that scattering in water column can provide a good fit to data at long ranges (more than 6 km). However, to fit the data level, volume scattering strength in water column should be somewhat higher than typical. Unfortunately, there is no any available TREX ground truth data for scattering in water column at these ranges.

Next case to consider is volume scattering in the sediment. As an initial step on this way, the bottom volume scattering coefficient was assumed to be range-independent. The results are shown in Figure 3. Then a possibility of a smooth range-dependence of M_V was considered to reduce the model-data difference. This resulted in estimated/inferred range-dependence M_V shown in Figure 4. Corresponding corrected reverberation model-data comparison is shown in Figure 5. A similar procedure was performed for analysis of after storm reverberation. Initial model-data comparison (for range independent M_V) shows only a slight discrepancy at small ranges, which was easily compensated by a correspondingly slight range-dependence of sediment volume scattering strength shown in Figure 6. Then model-data comparison, shown in Figure 7, becomes reasonably good.

Comparison of Figure 4 and Figure 6 may help to understand nature of the environmental impact of the storm on reverberation. Such impact could result from dynamical mixing of the sediment and consequent smoothing of the range dependence of the strength of surficial sediment heterogeneity along the observation path. Importantly, same conclusions would be reached if the range-dependence

of local roughness scattering is considered. In more detail, this will be described in a separate paper, Ivakin (2015c).

In addition, to ensure that the two runs, #17 and #79, see Figure 1, used here for model-data comparisons, are indeed representative of a more comrehensive data set, reverberation data from five more runs which recently became available, Tang (2015), were considered in Ivakin (2015b). They were added to previous two runs and confirm the general effect of the storm seen in Figure 1. This suggests that above-shown model-data comparison, as well as conclusions based on this comparison, will stay reasonable for a more comprehensive TREX13 data analysis.

IMPACT/APPLICATIONS

This research is to contribute to further development of shallow water reverberation models and codes. In particular, it is aimed to developing a robust model (potentially a tool) for prediction and interpretation of reverberation in complex (range-dependent, potentially 3D-dependent) waveguides. The developed Green's function modeling approach allows fast estimations of propagation and reverberation in shallow water. The approach also addresses a basic science question: how scattering solutions obtained for free space (or measured in direct-path, short-range conditions) can be incorporated into long-range reverberation in bounded and complicated environments, such as shallow water or deep-water waveguides, where effects of multiple interactions with boundaries and volume heterogeneities must be taken into account, providing both sufficient accuracy and speed of calculations.

Computer simulations with environmental inputs typical for shallow water have been conducted. Capabilities of this modelling approach and developed codes to provide a reasonable interpretation of TREX2013 reverberation data were demonstrated and discussed. Based on these results, future research may address several science issues, which appeared to be important for better understanding TREX2013 data:

- To account for sediment lateral variability, mud patches/strips, using more advanced PE codes for Green's function (here only the case of Pekeris waveguide was considered);
- To analyze environmental and acoustic data to get inputs describing spatial variability of the sediment (shell content, interface roughness and heterogeneity spectra), as well as water column (fish, bubbles);
- To extensively support TREX13 data analysis, including data obtained for whole mid-frequency range, 1-10 kHz, and all other azimuthal angles (here only a subset of data at 3.4-3.5 kHz and one azimuthal direction was considered).

Several journal papers are in preparation for submission in near future, based on results and ideas of this research, briefly discussed and presented in this report. They are tentatively shown as Ivakin (2015c, 2015d, 2015e, 2015f).

RELATED PROJECTS

This research is built on results of previous and current projects on shallow water propagation, reverberation and scattering in heterogeneous marine environments funded by ONR-OA, and assumes

a close collaboration with TREX13 PIs, Drs. Todd Hefner, DJ Tang, Kevin Williams, and other investigators working in this field. This research is also closely related to Todd Hefner's effort on high-frequency acoustic propagation and scattering in heterogeneous sediments.

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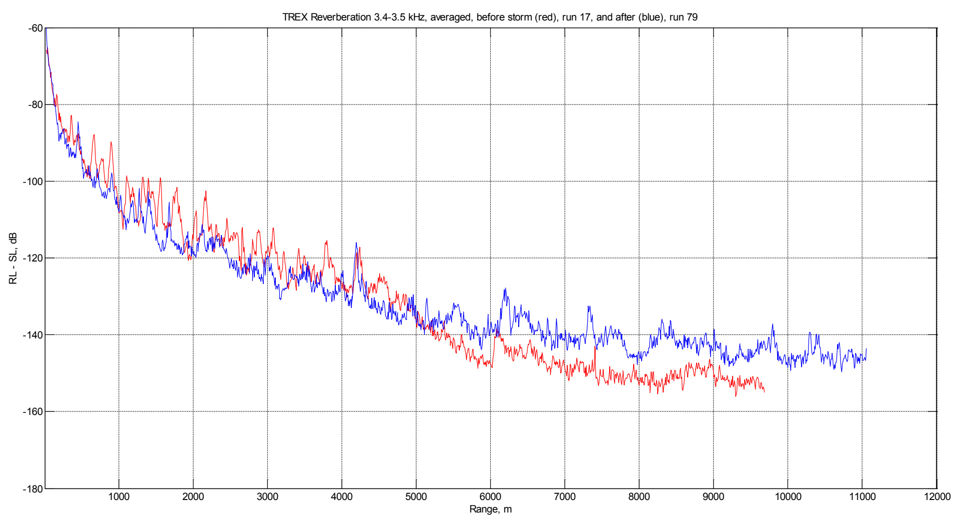

Figure 1: TREX13 normalized reverberation intensity, RL-SL, at 3.4-3.5 kHz, for two runs, before (red) and after (blue) storm.

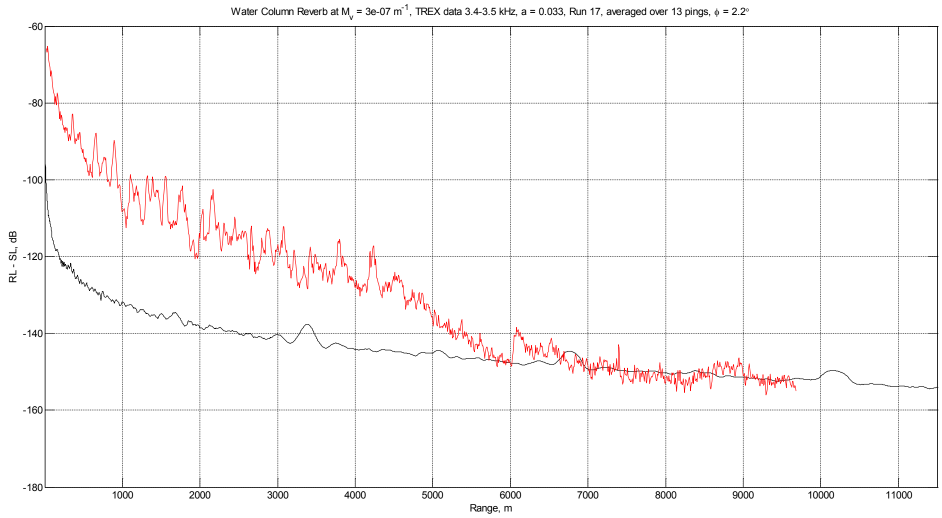

Figure 2: TREX13 normalized reverberation intensity, RL-SL, at 3.4-3.5 kHz, measured before storm (red), compared to model result calculated for scattering in water column with volume scattering coefficient $M_V = 3\times10^{-7}\ m^{-1}$.

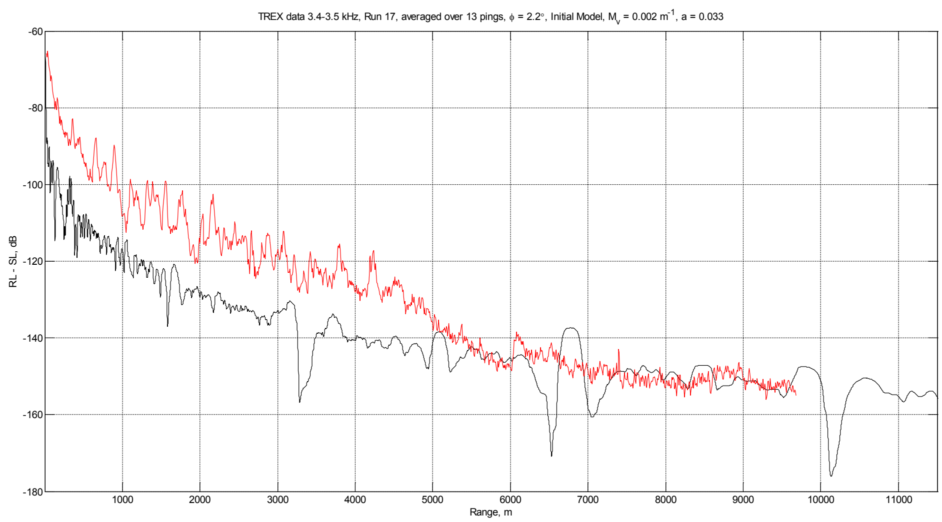

Figure 3: TREX13 normalized reverberation intensity, RL-SL, at 3.4-3.5 kHz, measured before storm (red), compared to that calculated for volume scattering in sand bottom (range-independent) with $M_V = 0.002\ m^{-1}$.

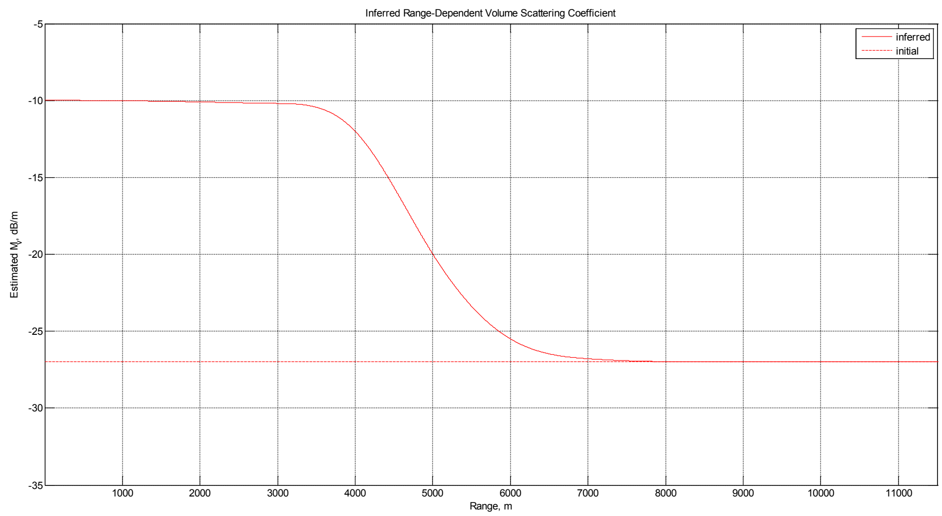

Figure 4: A correction made for range-dependence of local volume scattering strength in TREX13 sand bottom before storm.

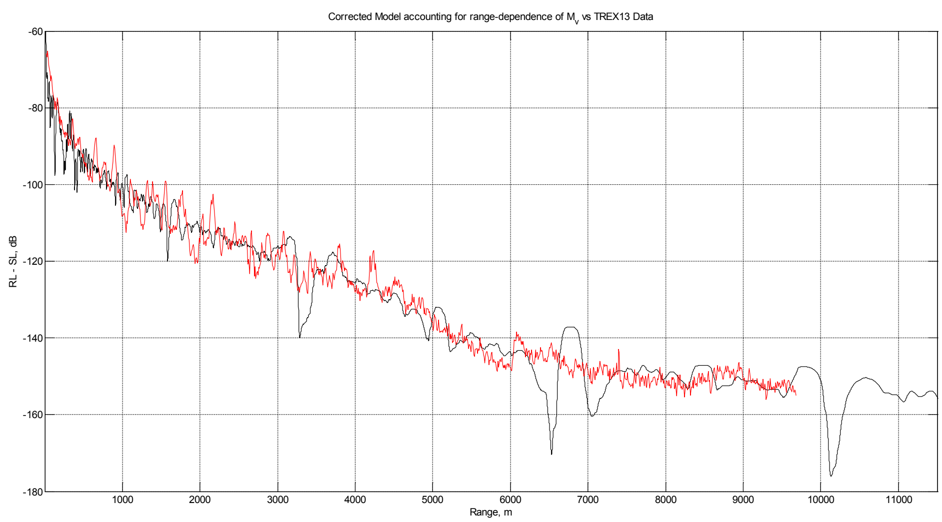

Figure 5: TREX13 normalized reverberation intensity, RL-SL, at 3.4-3.5 kHz, measured before storm, compared to that calculated for volume scattering in sand bottom with corrected range-dependent volume scattering strength shown in Figure 4.

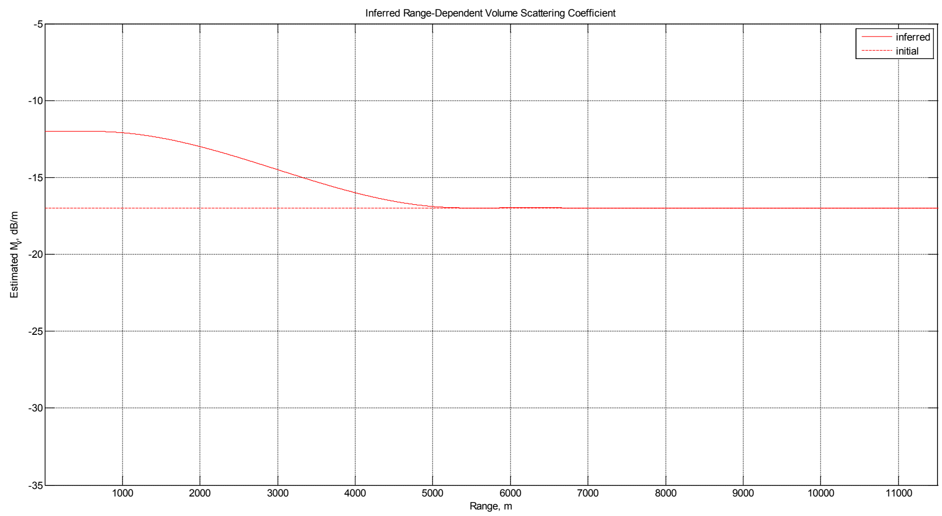

Figure 6: A correction made for range-dependence of local volume scattering strength in TREX13 sand bottom after storm.

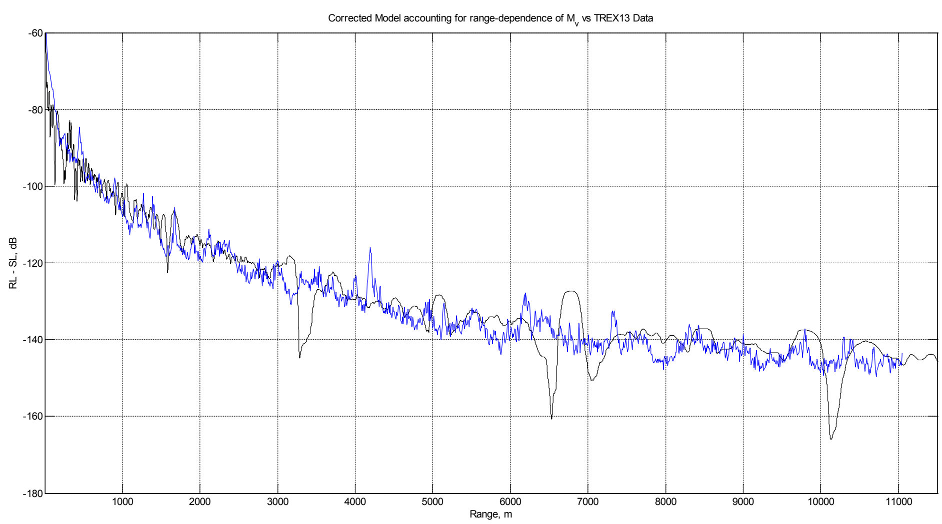

Figure 7: TREX13 normalized reverberation intensity, RL-SL, at 3.4-3.5 kHz, measured after storm (blue), compared to that calculated for volume scattering in sand bottom with corrected range-dependent local volume scattering strength shown in Figure 6.